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END-TO-END RMS ERROR TESTING ON A CONSTANT BANDWIDTH FM/FM SYSTEM

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16. ABSTRACT

This paper describes end-to-end root-mean-square (rms) tests performed on a constant bandwidth (CBW) FM/FM system with various settings of system parameters (transmission noise, system data loading, data shapes, etc.). The testing technique employed is that of sampling, digitizing, delaying, and comparing the analog input against the sampled and digitized corresponding output. Total system error was determined by fully loading all channels with band-limited noise and conducting end-to-end rms error tests on one channel. Tests were also conducted with and without a transmission link and plots of rms errors versus receiver signal-to-noise (S/N) values were obtained. The combined effects of intermodulation, adjacent channel crosstalk, and residual system noise were determined as well as the single channel distortion of the system.

Note: The activity reported here is a portion of the effort under RTOP 150-22-03, Mission Spacecraft Compatibility with Telemetry Data Relay Satellite System, and was accomplished at the Astrionics Laboratory.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

TECHNICAL MEMORANDUM X- 64647

END-TO-END RMS ERROR TESTING ON A CONSTANT BANDWIDTH FM/FM SYSTEM

INTRODUCTION

End-to-end root-mean-square (rms) tests were performed on a constant bandwidth (CBW) FM/FM system. The test philosophy, techniques, and actual test procedures are outlined. The different ways distortion may be introduced on a signal are described as well as the various tests performed and the data taken. Total system error was determined by fully loading all channels with band-limited noise and conducting end-to-end rms error tests on one channel. The combined effects of intermodulation, adjacent channel crosstalk, and residual system noise were determined as well as the single channel distortion of the system. Tests were also conducted with and without a transmission link and a plot of rms error versus receiver signal-to-noise (S/N) values was obtained.

The CBW FM/FM system under test is relatively simple in concept; consequently little space is devoted to its explanation. Eleven channels are employed as shown in Figure 1 (note that no translation devices are used). These eleven channels are fed into a mixer amplifier and the output of the mixer amplifier is then fed into a radiofrequency (RF) assembly. After the signal has passed through the transmitter and power amplifier, the channels are demultiplexed and the individual data signals are regained by using bandpass filters and frequency discriminators. The tested CBW FM/FM system is shown in Figure 1.

TEST PHILOSOPHY, TECHNIQUES, AND PROCEDURES

The end-to-end rms testing of the CBW FM/FM system is simple in concept. The input is sampled at time t_1 and digitized, the output is sampled at $t_1 + \tau$ (τ being the system delay) and digitized, and the two samples are compared. The differences are squared and divided by the discrete sample length (1024 in the experiment) thus yielding D^2/N or the mean squared error. Figure 1 outlines this setup. As would be expected, the experiment is conceptually simple, but many operations are required. The Systems Engineering Laboratory (SEL) telemetry data analysis system (TDAS) is an ideal

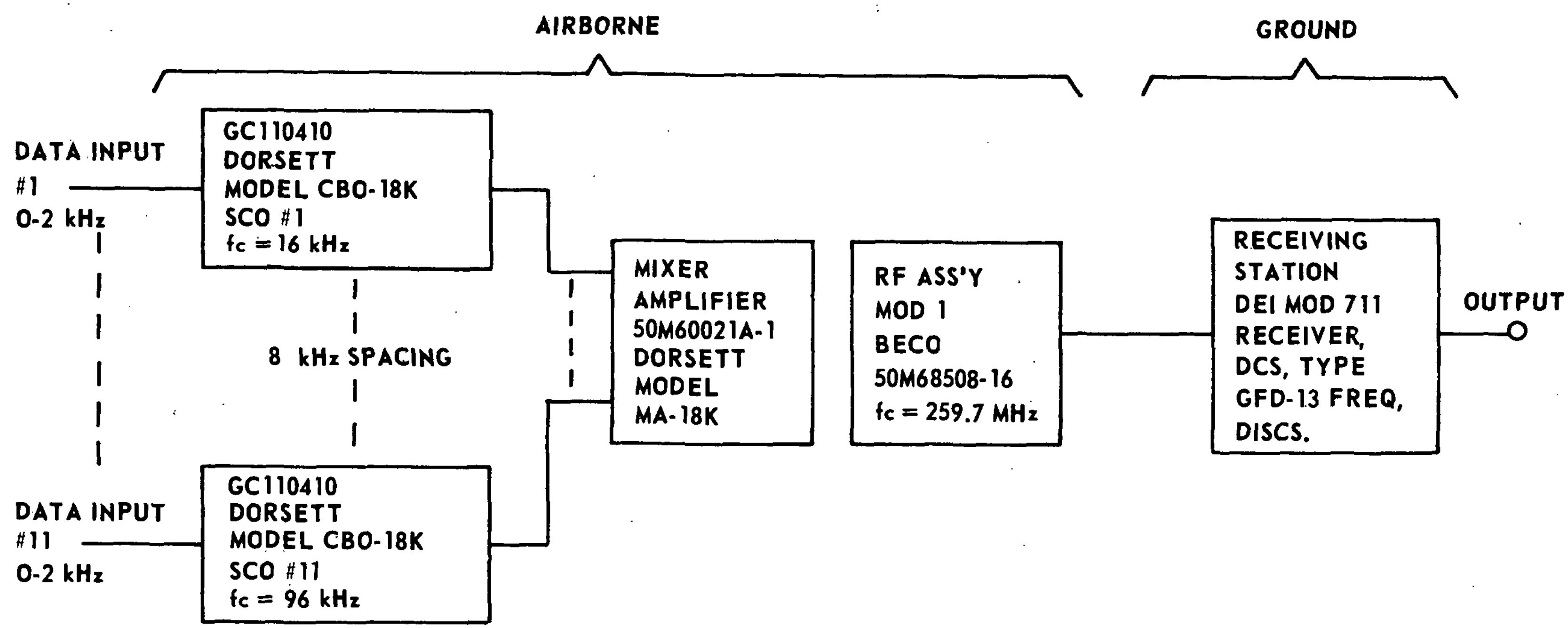

Figure 1. CBW FM/FM system.

instrument to do these operations as its speed of operation, input and output devices, and ease in programing are all designed to perform these types of test calculations.

The data used for the tests were band-limited white noise. The spectral shapes are outlined in Figure 2. The amplitude probability density was approximately Gaussian, but with a 4δ limit. The rolloff was obtained by feeding the effectively flat spectrum of white noise into a 3-pole lowpass Butterworth filter (18 dB per octave). The "corner" or 3 dB points for the filters were variable.

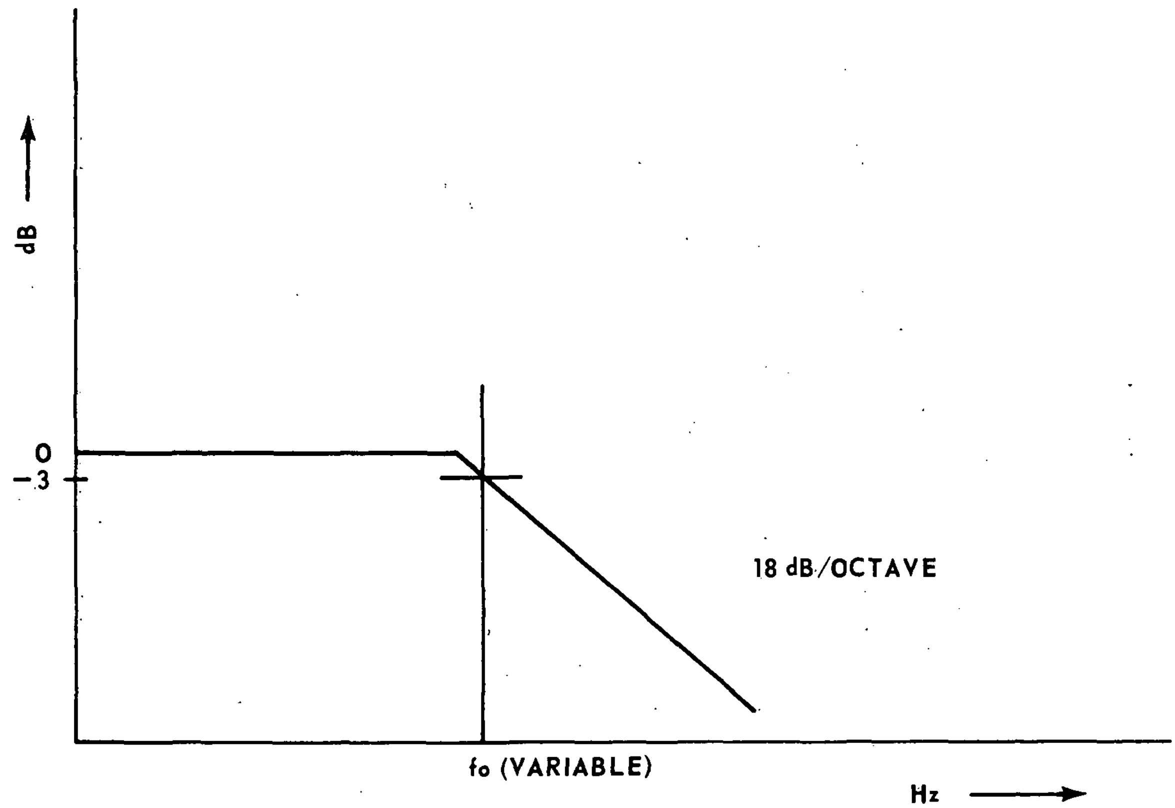

Figure 2. Filtered white noise data spectra.

The sampling rate necessary to perform the testing is a function of the system delay. The actual repetition time of samples was selected to be ten times the system delay (τ) to assure that independent samples were taken.

The discussion of the CBW system has been fairly well covered. The one item not discussed in the airborne system involves the preemphasis curve used on the eleven subcarrier oscillators (SCOs). The basic criterion used in establishing the preemphasis curve was that the SCO levels were adjusted such that a constant S/N ratio (in the receiver) for all SCO bands would be obtained. This criterion was established with a given signal level into the receiver. Table 1 outlines the exact values used.

TABLE 1. PREEMPHASIS SETTINGS FOR THE TESTED CONSTANT BANDWIDTH SYSTEM

CHANNEL	FREQUENCY (kHz)	DEVIATION (kHz)
- -	16.00	14
- -	24.00	16
- -	32.00	17
- -	40.00	18
- -	48.00	19
- -	56.00	20
- -	64.00	21
- -	72.00	22
- -	80.00	23
- -	88.00	24
- -	96.00	25

A critical element of the overall system was the ground station which was composed of a receiver and discriminator (Fig. 1). The receiver, a late version produced by Defense Electronic, Inc. (model 711), has a pluggable intermediate frequency (IF) filter (3.3 MHz, 1.0 MHz, 300 kHz, or 100 kHz). The discriminator, a late version phase-lock type produced by Data Controls Systems, Inc. (model GFD-13), has pluggable bandpass filters and data filters. The bandpass filter used was 40 kHz ±2 kHz in all tests, while the lowpass output filter was either a 2-kHz or a 4-kHz constant amplitude filter (the exact filter is specified with the experiment data tabulation).

CAUSES OF SIGNAL DISTORTION

A signal transmitted through a telemetry channel undergoes distortion caused by effects within the channel as well as interchannel effects. Tests were performed to determine the contribution of each of these effects to the total distortion. All potential sources of distortion were considered in this study except for the error produced by the propagation medium which was removed by hard-wiring the transmitter to the receiver through suitable attenuators.

Sources of Distortion

Airborne System. Distortion of the data signal is caused by nonlinearities in the amplitude and phase response of the SCO lowpass filter. Additional distortion occurs because subcarrier harmonics and their associated sidebands are not infinitely attenuated. The result is an overlapping of subcarrier spectra when the SCO outputs from the various channels are combined in the linear mixer. The mixer-amplifier and FM transmitter provide still other sources of error called intermodulation distortion.

Ground System. Any noise created within the airborne system, transmission medium, or "front end" of the ground receiver is combined with the RF signal prior to demodulation. The receiver limiter eliminates the amplitude variation caused by the noise, but the phase variation results in an error in frequency. In FM, this phase variation appears as amplitude distortion on the demodulated signal output.

Additional errors are introduced by the channel-selecting bandpass filter. Since attenuation is not infinite outside the passband, some of the frequency components of the adjacent channels are transmitted along with those of the desired signal. The bandpass filter also clips some of the higher-order sidebands of the desired signal. Further distortion results from the nonlinear amplitude and phase response of this filter.

Distortion is also introduced by the subcarrier discriminator. Any nonlinearity in the frequency/amplitude transfer function will cause errors as well as any nonlinearity in the amplitude and phase characteristics of the lowpass output filter.

TEST RESULTS

Results are shown in Figures 3, 4, and 5 for the channel centered at 40 kHz. In Figures 3 and 4, the errors resulting from RF noise are eliminated by connecting the output of the mixer-amplifier directly to the ground discriminator. Test data were taken for both the 2-kHz and 4-kHz lowpass output filters while the channel-selecting bandpass filter was set at 40 kHz ±2 kHz

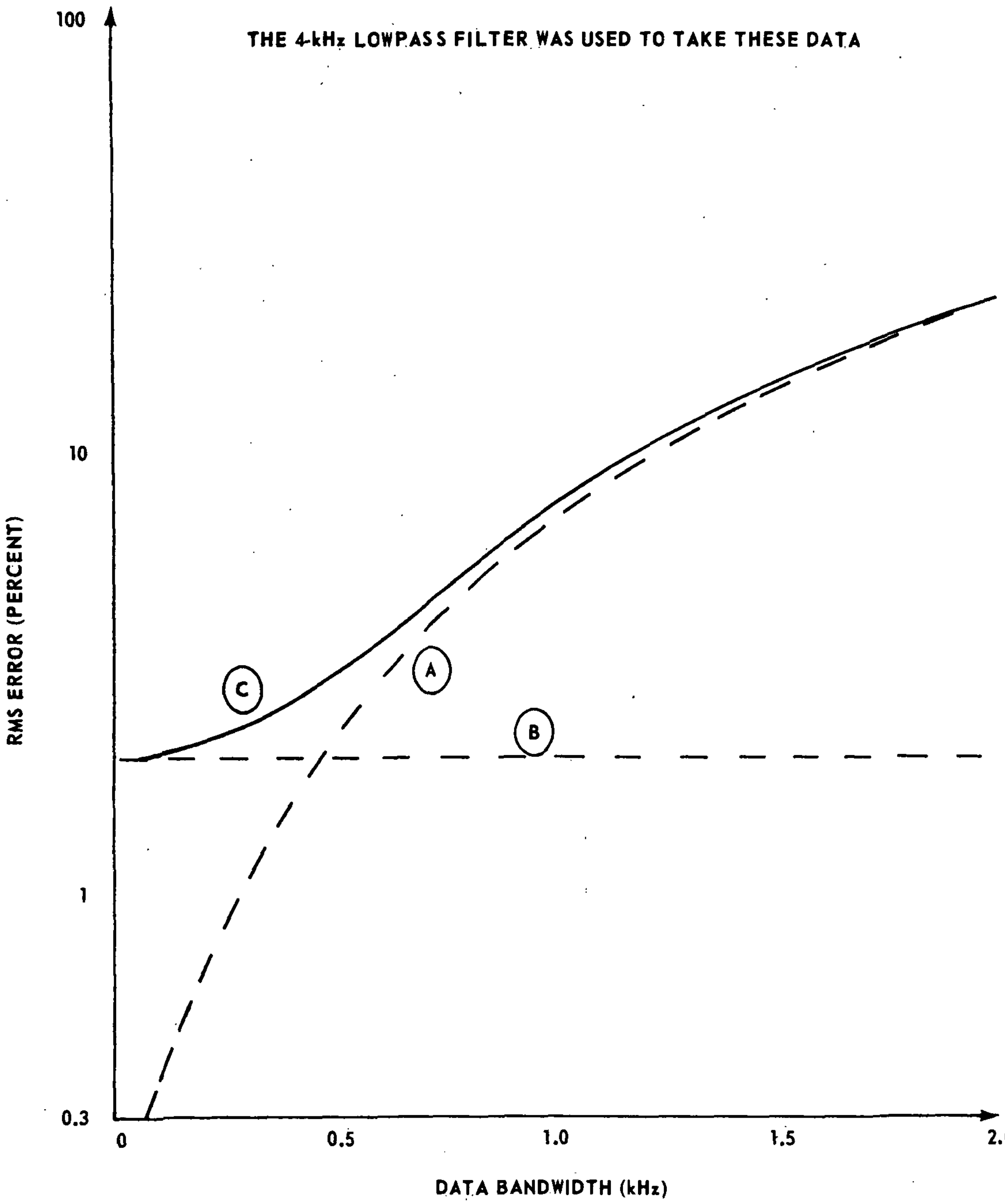

Figure 3. Constant bandwidth system using a 2-kHz lowpass output filters — rms error versus data bandwidth.

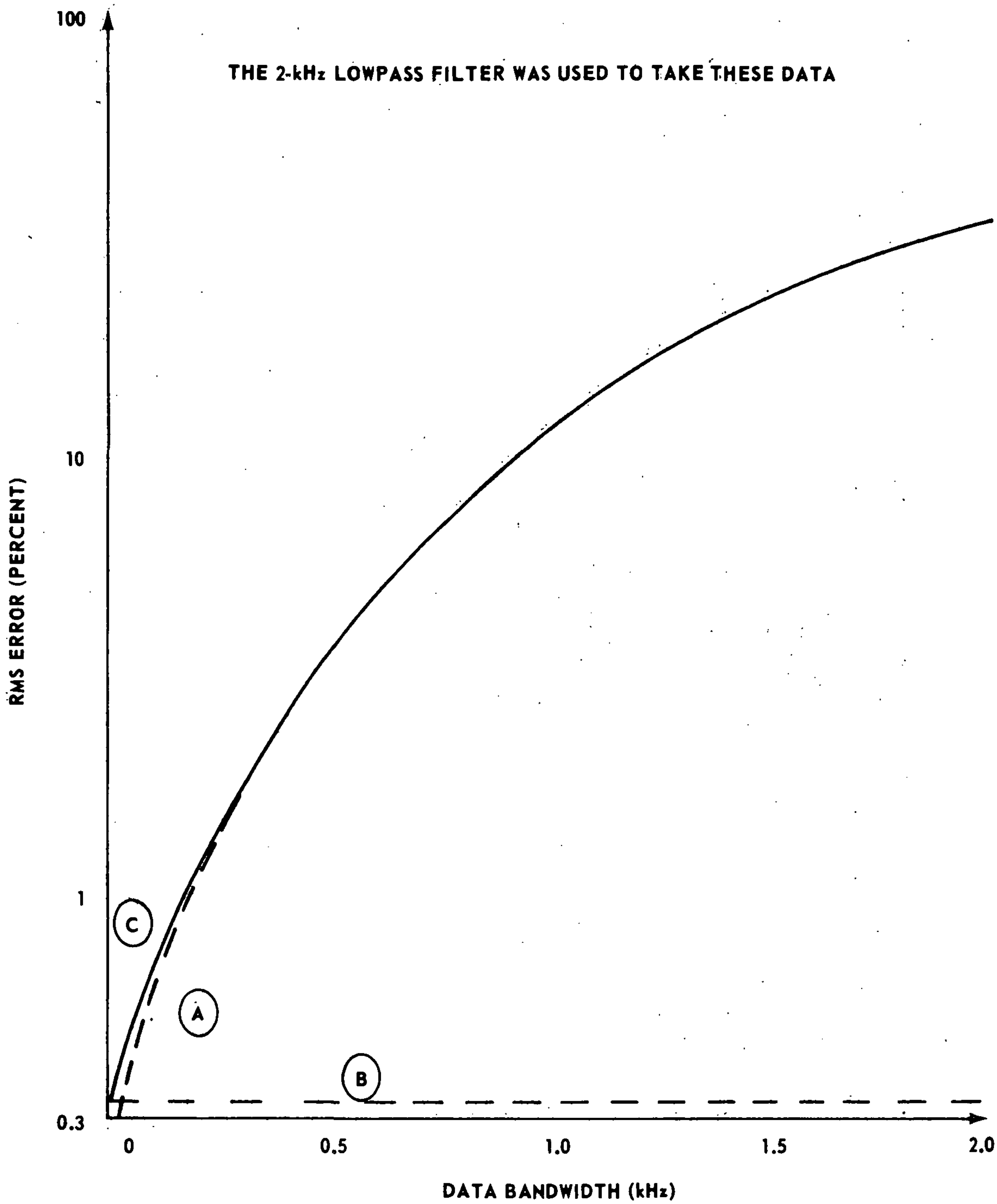

Figure 4. Constant bandwidth system using 2-kHz lowpass output filters — rms error versus data bandwidth.

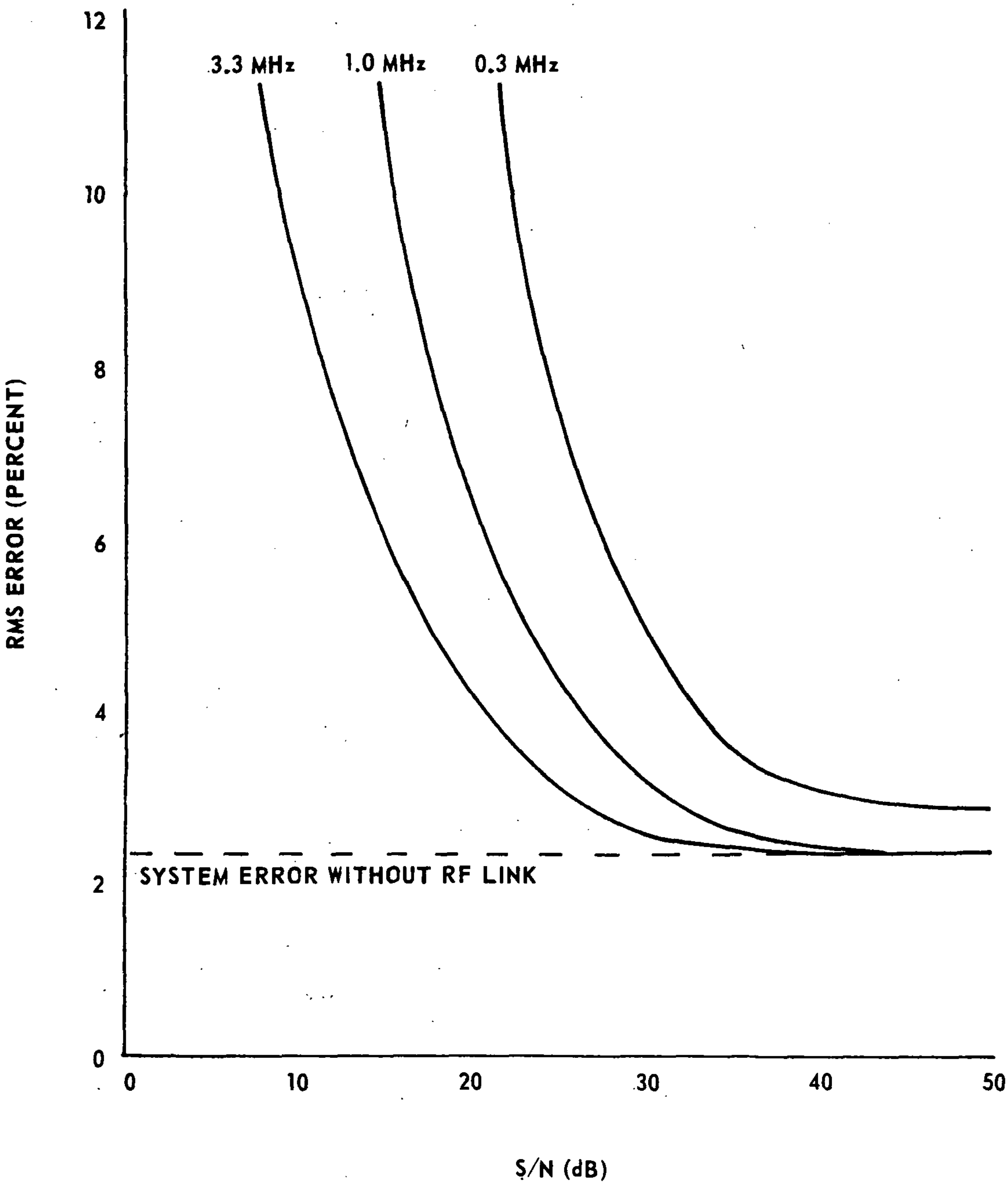

Figure 5. Performance of a CBW FM/FM system as a function of receiver IF S/N ratio.

for all measurements. In all cases, the random data were amplitude adjusted to 0.625 volts rms (5 volts peak-to-peak). The error readings are given in percent normalized to the rms full scale of 0.625 volts. With the 4δ data used in this experiment, this is a factor of eight more than comparable peak-to-peak error plots.

The first tests performed eliminated the effects caused by interference from other channels by disconnecting the SCOs from the remaining channels in the system (Fig. 6 and Table 2). The increase in waveform distortion with data bandwidth (Curve A in Figs. 3 and 4) can be attributed primarily to non-linearities in the transfer characteristics of the various filters in the system. Also, as the input signal bandwidth approached that of the channel, the higher frequency components were severely attenuated, resulting in a further increase in distortion. Curve B represents the error when all the other channel SCOs are present and are modulated with third-order random data band-limited to 2 kHz, while 2.5 volts dc are applied to the test channel (Fig. 7 and Table 3). The distortion caused by effects from the other channels was found to have an rms value of 1.96 percent for the 4-kHz output filter and 0.33 percent for the 2-kHz output filter. Curve C of Figures 3 and 4 represents the total waveform distortion in the 40-kHz test channel when all channels in the system contain third-order random data (Fig. 8 and Table 4). The data bandwidth for the test channel is varied from dc to 2 kHz while bandwidth for the other channels are fixed at 2 kHz. Mathematically, points on curve C may be found by rms summing of corresponding points on curves A and B.

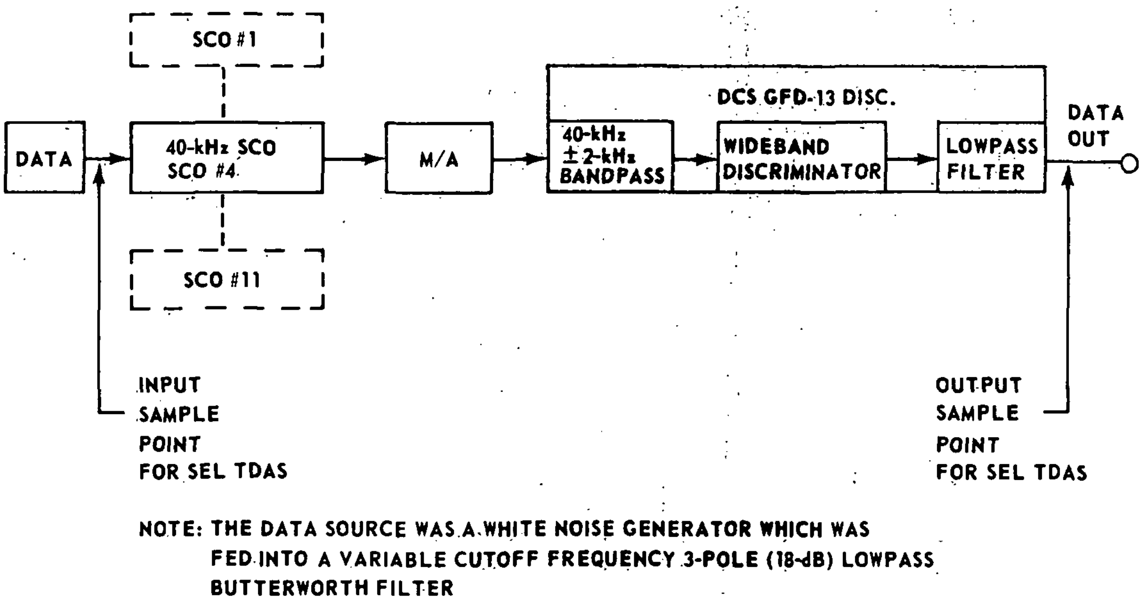

Figure 6. Single channel distortion test.

TABLE 2. DATA FROM SETUP OF FIGURE 6

f_{data}	System Delay (μs)	D^2/N	$(D^2/N)^{1/2}$	(Counts)	Normalized Error (%)
A: 4-kHz THIRD ORDER LOWPASS OUTPUT FILTER					
500 Hz	456	7.93			
		8.40			
		8.74			
		8.23			
		8.80	2.90	14.50	2.32
1000 Hz	461	79.5			
		72.1			
		86.5			
		78.5			
		79.6	8.90	44.50	7.12
1500 Hz	462	288.1			
		288.1			
		295.4			
		289.0			
		294.5	17.0	85.00	13.6
2000 Hz	462	750.4			
		739.8			
		713.9			
		682.9			
		729/2	26.8	134.0	21.5
B: 2-kHz THIRD ORDER LOWPASS OUTPUT FILTER					
500 Hz	644	18.31			
		17.33			
		16.94			
		17.56			
		16.93	4.17	20.85	3.34
1000 Hz	649	221.8			
		205.7			
		198.7			
		214.4			
		209.2	14.48	72.40	11.77
1500 Hz	667	--	--	--	23.92

NOTES 1. 40-kHz ±2-kHz and 4-kHz lowpass constant amplitude filters on the discriminator.
2. N = 1024 samples.
3. The data shown result in curve A of Figure 6.
4. The counts figure is the results of multiplying the $(D^2/N)^{1/2}$ by the 5 mV bit transfer function of the sampling system.
5. The normalized error (%) is the result of dividing the counts by 625.

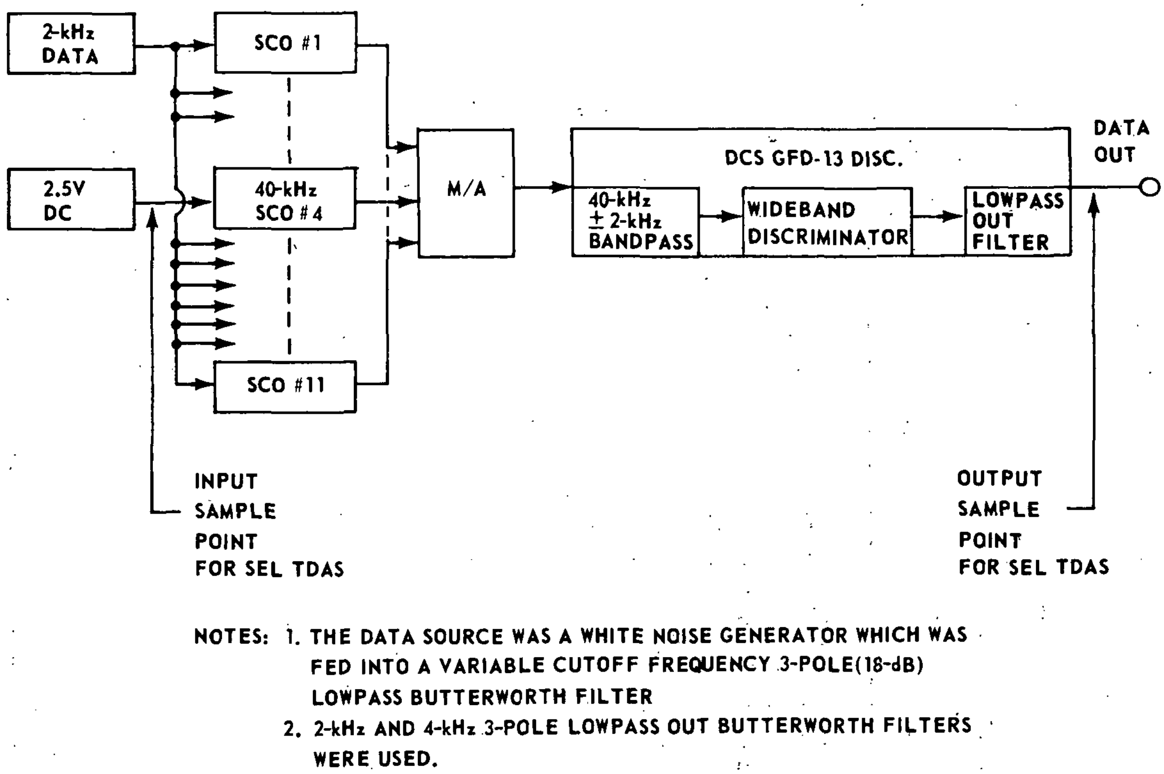

Figure 7. Distortion present in unmodulated channel.

In Figure 5, the effects of noise in the RF transmitter and receiver are depicted. The test channel (40 kHz) contained third-order random data band-limited to 500 Hz, while the other channels remained in the static condition (2.5 volts dc). The transmitter output was hard-wired through a series of variable attenuators to the receiver input. S/N ratio, read at the 10-MHz linear output of the receiver, was varied by inserting different attenuators between the transmitter and the receiver, while the rms error was measured (see Figure 9 for test setup). As shown, results were obtained for three different IF filters. For the 3.3-MHz filter and the 1.0-MHz filter, as the S/N ratio was made larger, the error asymptotically approached 2.32 percent, the value measured when the transmitter and receiver were omitted from the circuit. In the case of the 0.3-MHz filter, as the S/N ratio was made larger, the error leveled off at 2.8 percent, revealing that more of the outermost side-bands of the transmitted spectrum were lost in the filtering process. The data taken for the various S/N and IF bandwidth conditions are outlined in Table 5.

TABLE 3. DATA FROM SETUP OF FIGURE 7

A: 4-kHz THIRD ORDER LOWPASS OUTPUT FILTER							
f_{data}	(Adjacent Channels)	f_{data}	(Test Channel)	D^2/N	$(D^2/N)^{1/2}$	(Counts)	Normalized Error (%)
2000 Hz		D-C		5.72 6.22 5.89 6.30 6.00	2.45	12.25	1.96
B: 2-kHz THIRD ORDER LOWPASS OUTPUT FILTER							
2000 Hz		D-C		0.146 0.182 0.146 0.190	0.407	2.035	0.326

NOTES 1. 40-kHz ±2-kHz and 4-kHz lowpass constant amplitude filters on the discriminator.
2. N = 1024 samples.
3. The data shown result in curve B of Figure 7.
4. The counts figure is the result of multiplying the $(D^2/N)^{1/2}$ by the 5 mV/bit transfer function of the sampling system.
5. The normalized error (%) is the result of dividing the counts by 625.

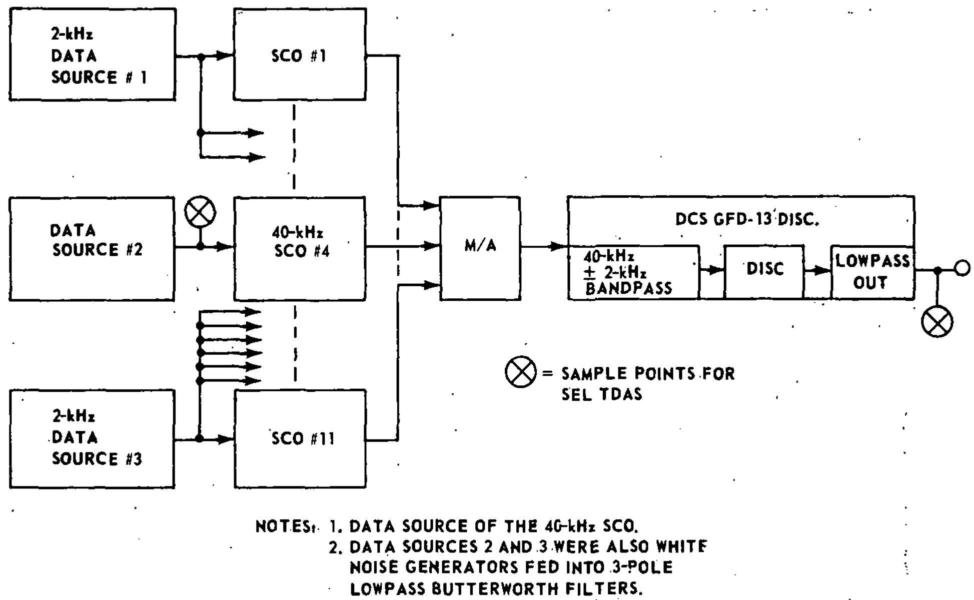

Figure 8. Total waveform distortion with system fully loaded.

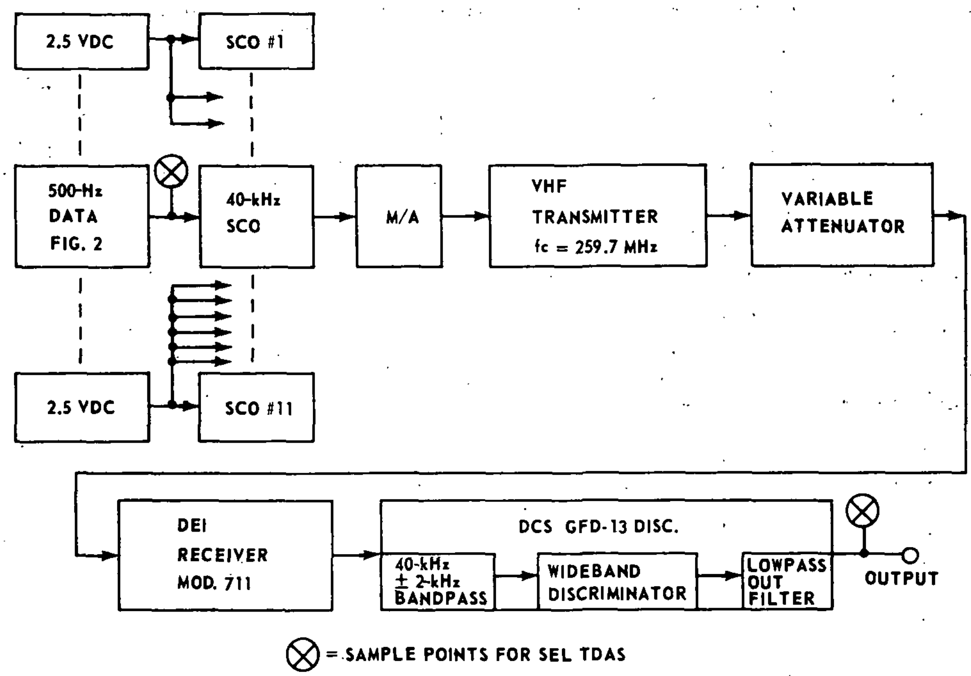

Figure 9. Tests to determine effects of transmission noise — one channel loaded.

TABLE 4. DATA FROM SETUP OF FIGURE 8

f_{data}	System Delay (μs)	D^2/N	$(D^2/N)^{1/2}$	(Counts)	Normalized Error (%)
A: 4-kHz THIRD ORDER LOWPASS OUTPUT FILTER					
500 Hz	456	14.94			
		13.52			
		14.89			
		12.86			
		14.60	3.75	18.75	3.01
1000 Hz	461	87.9			
		87.8			
		88.6			
		87.1			
		89.9	9.39	46.95	7.52
1500 Hz	462	274.9			
		303.4			
		292.6			
		286.8			
		291.5	17.0	85.0	13.62
2000 Hz	462	746.9			
		768.8			
		719.7			
		739.6			
		739.3	27.4	137.0	21.80
B: 2-kHz THIRD ORDER LOWPASS OUTPUT FILTER					
500 Hz	644	18.86			
		18.97			
		18.30			
		17.45			
		17.28	4.25	21.25	3.41
1000 Hz	649	211.4			
		219.8			
		224.0			
		211.6			
		216.1	14.7	83.5	11.77
1500 Hz	667	915.7			
		888.8			
		851.2			
		930.5			
		885.6	29.9	149.5	23.92

NOTES 1. N = 1024 samples.
2. The data taken result in curve C of Figure 8.
3. The counts figure is the result of multiplying the $(D^2/N)^{1/2}$ by the 5 mV/bit transfer function of the sampling system.
4. The normalized error (%) is the result of dividing the counts by 625.

TABLE 5. S/N LEVELS VERSUS RMS ERROR

Receiver Meter Signal Above Noise (dB)	S + N (dB)	N (dB)	IF Bandwidth (MHz)	System Delay (μs)	D^2/N	Percent Error	Adjusted S/N (dB)
Without RF link, the delay is 456 μs and the error is 2.44%.							
46	-10.3	-81	3.3	456	8.96		
					10.06		
					9.74		
					9.87		
					9.12	2.47	40.3
51	-10.0	-78	1.0	460	9.62		
					9.67		
					9.53		
					9.46		
					9.85	2.48	42.8
54	-9.5	-77	0.3	467	13.82		
					12.66		
					12.33		
					14.46		
					13.51	2.92	47.5
59	-9.9	-86	3.3	459	9.00		
					8.78		
					9.63		
					9.98		
					9.11	2.44	45.7
63	-9.8	-84	1.0	460	9.23		
					9.79		
					9.28		
					9.43		
					8.70	2.44	49.0
65	-9.7	-83	0.3	467	13.35		
					14.07		
					12.61		
					14.16		
					14.54	2.96	53.3
35	-10.7	-7.5	3.3	459	10.22		
					9.61		
					10.17		
					10.46		
					9.78	2.54	33.9
40	-10.5	-72	1.0	460	10.88		
					10.89		
					10.81		
					11.61		
					10.44	2.64	36.3
43	-10.4	-71	0.3	467	14.78		
					15.73		
					16.18		
					15.45		
					15.35	3.15	40.6
Without the RF link, the delay is 456 μs and the error is 2.31%.							
29	-11	-70.7	3.3	459	10.98		
					11.48		
					11.34		
					10.99		
					10.13	2.90	29.3
34	-10.8	-67.5	1.0	460	12.21		
					13.73		
					13.87		
					12.55		
					13.45	2.90	31.5
36	-10.7	-66	0.3	467	18.59		
					19.04		
					19.05		
					19.61		
					19.54	3.50	35.3

TABLE 5. (Concluded)

Without the RF link, the delay is 456 μs and the error is 2.30%.							
24	-11.2	-67.6	3.3	459	13.33		
					14.23		
					14.20		
					13.19		
					13.15	2.95	26.0
30	-11.0	-65.0	1.0	460	16.88		
					17.86		
					17.43		
					17.28		
					16.70	3.32	29.8
32	-10.8	-64	0.3	467	25.13		
					23.70		
					25.19		
					25.89		
					24.73	3.99	33.2
Without the RF link, the delay is 456 μs and the error is 2.32%.							
20	-11.4	-65	3.3	459	19.03		
					18.09		
					19.43		
					19.21		
					18.85	3.48	23.2
26	-11.0	-62.5	1.0	460	24.77		
					24.67		
					24.16		
					23.17		
					23.00	3.92	26.2
30	-10.9	-61.5	0.3	467	33.45		
					35.55		
					32.26		
					33.48		
					33.93	4.65	30.6
Without the RF link, the delay is 456 μs and the error is 2.34%.							
10	-11.7	-58.5	3.3	459	53.67		
					56.72		
					59.78		
					59.05		
					58.10	6.06	15.0
18	-11.4	-57.0	1.0	460	72.92		
					65.44		
					66.59		
					68.54		
					62.80	6.56	19.75
21	-11.1	-56.5	0.3	467	80.78		
					91.44		
					85.17		
					86.83		
					75.32	7.33	24.65
6	-12.3	-55.0	3.3	459	133.84		
					126.30		
					128.66		
					134.63		
					136.22	9.18	9.75
13	-11.6	-54.0	1.0	460	131.50		
					143.84		
					134.03		
					133.74		
					137.58	9.33	16.00
17	-11.3	-54.0	0.3	467	174.88		
					158.94		
					168.03		
					164.91		
					170.14	10.35	22.00

NOTES 1. The setup of Figure 9 was used to take these data.
2. The D^2/N column is particularly interesting as it shows the dispersion of samples. Each entry is in itself 1024 samples.
3. The percent error is tabulated from the D^2/N entries which are averaged and the square root taken. Then this value is multiplied by 5 mV/count conversion factor and the result multiplied by 100 and divided by 625 mV to get percent error.
4. The data of this table are plotted in Figure 5.

CONCLUSION

The curves of Figures 3, 4, and 5 should allow one to make some basic parameter estimations on new (or existing) systems. The overall accuracy on which these figures are based is better than 99.75 percent with the bulk of the inaccuracy being lost in two analog-to-digital conversions (after the analog data are sampled, they are digitized for SEL telemetry data analysis system manipulations).

APPROVAL

END-TO-END RMS ERROR TESTING ON A CONSTANT BANDWIDTH FM/FM SYSTEM

By G. R. Wallace and W. E. Salter

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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